Probabilistic risk analysis of building columns to gas pipeline explosions

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Abstract: The failure of natural-gas pipelines often induces heavy damage to buildings. Proper safety distances should thus be defined as land-use policy to ensure that an acceptable risk level is not exceeded. In this paper, such an issue is addressed for existing reinforced concrete framed buildings. A probabilistic risk analysis procedure is proposed to estimate the annual probability of damage to reinforced concrete columns associated with high-pressure natural-gas pipeline explosions. Physical features such as the gas jet release process, flammable cloud size, blast generation and propagation, and explosion effects on building columns are considered and evaluated through the SLAB integral model, multi-energy method and structural blast fragility surfaces. Failure probability is estimated through Monte Carlo simulation where the main uncertainties are taken into account. Minimum pipeline-to-building safety distances are derived in several environmental conditions, allowing a risk-informed land-use planning and performance-based design/assessment of pipelines and buildings.

Keywords: natural-gas pipelines; pipeline failure; explosions; reinforced concrete columns; pressure-impulse diagrams; structural damage; probabilistic risk assessment; Monte Carlo simulation; multi-energy method; annual damage risk.


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1 Introduction

The consequences of damage to a high-pressure pipeline that carries out natural gas through rural and urban areas can be significant not only in terms of direct and indirect economic losses, but also on people and built environment. As a matter of fact, the presence of a gas transmission pipeline induces a non-zero blast hazard that should be taken into account when assessing the safety level of people and facilities in a given area. The level of risk will depend on the mode of line failure (i.e. leak or rupture), the nature of gas discharge (i.e. vertical or inclined jet, obstructed or unobstructed jet) and the time to ignition (i.e. immediate or delayed). Quantitative Risk Analysis (QRA) is an effective methodology to rationally evaluate risk in probabilistic terms by accounting for its different components, namely hazard, vulnerability and exposure. As far as explosions induced by gas pipeline failure are concerned and regardless of the exposure level, QRA consists of the following steps: (1) the assessment of blast hazard, that is the probability of exceeding a prescribed level of blast intensity in a given spatio-temporal scale; (2) the evaluation of blast vulnerability of elements at risk; and (3) the estimation of risk as a convolution of hazard and vulnerability. Assessing the blast risk allows decision-makers to prioritise their choices in order to reduce losses from future accidental events. Actually, several studies reported a significant number of gas explosions (Mazzolani, 2010; Konersmann et al., 2009), emphasising that appropriate safety levels for people and properties against these hazards are urgently needed. A report by the European Gas Pipeline Incident Data Group (EGIG, 2013), which currently is a cooperation of 17 major gas transmission system operators in Europe, provided valuable data on rates and causes
of gas pipeline incidents. In that database, 1309 incidents are recorded over the period 1970–2013. Pipeline failure may be induced by several events (e.g. construction or operational errors, material defects, corrosion, man-made actions, soil failure under earthquakes), causing gas leakage, cloud formation and ignition. If a natural-gas explosion takes place, buildings located close or within the ignited gas cloud are subjected to high overpressure levels so their structural components may suffer extensive damage (Russo et al., 2014). Although blast overpressures vanish in a very short time, the failure of one or more individual components can propagate throughout the structure, eventually triggering a progressive collapse (Parisi and Augenti, 2012). This means that natural-gas pipeline explosions should be regarded as low-probability/high-consequence events similarly to other accidental or man-made actions.

In this paper, the authors present a probabilistic risk analysis procedure for the estimation of the annual failure probability of reinforced concrete (RC) columns which belong to buildings threatened by natural-gas pipeline explosions. According to the QRA approach, the failure probability is estimated by convolving blast hazard and fragility. The latter is defined as the conditional probability of failure given a blast intensity. Blast hazard is assessed through the multi-energy method (TNO, 2005), whereas fragility is estimated through Monte Carlo (MC) simulation. Blast capacity and demand are defined in the pressure–impulse space and a damage criterion is used to detect the occurrence of failure. Thousands of samples of RC columns, pipelines and environmental conditions were randomly generated. Blast hazard was assessed by assuming a horizontal gas jet from the leakage point of the pipeline. Compared to a previous research (Russo et al., 2014), this study takes into account the influence of wind and atmospheric stability. Wind velocities of 10, 20 and 30 m/s at a height of 10 m above ground were randomly produced, assuming a wind direction parallel to the gas jet and vertical logarithmic increase of wind velocity from the terrain roughness height. From a structural standpoint, different probability distributions were used to consider uncertainty in material and geometrical properties, as well as capacity models. Assuming a threshold probability of collapse for single RC columns, a (minimum) risk-targeted safety distance between pipeline and RC framed building can be derived. The threshold probability is the de minimis risk defining the acceptable risk level below which society normally does not impose any regulatory guidance. QRA was performed by assuming RC columns of gravity-load designed residential buildings, high-pressure transmission pipelines, two alternative blast strengths, and two possible Pasquill atmospheric stability classes. Risk-targeted safety distances may be used as thresholds below which existing RC framed buildings should be assessed against natural-gas pipeline explosions. The proposed methodology may be also applied to regulate the distance of new buildings from pipelines, and more in general for a risk-informed land-use planning.

2 Mathematical framework for quantitative risk analysis

Natural-gas explosions can induce local damage to individual structural components such as columns at the ground floor of a framed building structure. The propagation of that damage throughout the structure can result in a progressive collapse of the whole structural system or a part of it, hence producing significant consequences to property and people. From a phenomenological viewpoint, progressive collapse is then a cascade event conditioned upon local damage.
The annual probability of structural collapse under an extreme event $H$ can be estimated according to the risk analysis framework proposed by Ellingwood (2006) as follows:

$$
\Pr[C] = \Pr[C|LD] \Pr[LD|H] \lambda_H
$$

(1)

where $LD$ is the event that local damage occurs as a result of $H$, $C$ is the event of progressive collapse induced by $LD$, $\lambda_H$ is the mean annual rate of occurrence of $H$ that is numerically interchangeable with the annual probability of occurrence for randomly occurring events with rates less than $10^{-2}$/year, $\Pr[LD|H]$ is the conditional probability of local damage given $H$, and $\Pr(C|LD)$ is the conditional probability of progressive collapse given $LD$. This formulation allows one to design/assess a structure so that $\Pr[C] \leq p_{th}$ where $p_{th}$ is the de minimis risk or equivalently the maximum acceptable risk level below which society does not impose any regulatory guidance. This establishes a reliability-based criterion for design and assessment against single or multiple events. Among others, Pate-Cornell (1994) highlighted that $p_{th}$ is in the order of $10^{-7}$/year.

In this study, the annual risk is assessed at the local structural level, namely the scale of single reinforced concrete column which is the key component of reinforced concrete framed structures. Therefore, this research is focused on the following part of equation (1):

$$
\Pr[LD] = \Pr[LD|H] \lambda_H
$$

(2)

If one is interested in assessing the probability of progressive collapse, the following equation can be used:

$$
\Pr[C] = \Pr[C|LD] \Pr[LD]
$$

(3)

Assuming the operation of a natural-gas transmission pipeline to be the hazard source, the annual probability of local structural damage is further specialized to:

$$
\Pr[LD] = \Pr[LD|E] \Pr[E|R] \lambda_R
$$

(4)

where $E$ is the event that a natural-gas explosion occurs, $R$ is the event that a pipeline rupture takes place, and $\lambda_R$ is the annual mean rate of occurrence of the pipeline rupture. Statistical data have shown an overall mean annual failure rate of 0.351 per 1000 km over the period 1970–2013 and a mean annual failure rate over the past five years equal to 0.162 per 1000 km (EGIG, 2013). The value of 0.351/1000 km/year was used for the calculations discussed herein. The conditional probability $\Pr[LD|E]$ is the blast fragility of the structural component and $\Pr(E|R)$ is the blast hazard function that provides the probability of occurrence of the explosion given $R$. In the following, blast hazard is evaluated by means of the multi-energy method (TNO, 2005). The explosion generated by the natural-gas release is assumed to induce a two-component engineering demand on RC columns, which includes both peak overpressure and impulse. The latter is defined as the integral of the overpressure over the positive phase duration of the pressure time history. Actually, the positive phase of the blast loading process is that associated with most part of input energy which is responsible of structural damage. After that blast fragility is computed through standard MC simulation, the annual risk of blast damage to RC columns is estimated.
Figure 1 provides a sketch of the gas explosion generated by the pipeline failure and resulting loads on building columns, particularly at the ground floor. Figure 1 also shows the main parameters affecting the blast severity and damage which are taken into account in this research.

**Figure 1**  Schematic illustration of gas pipeline explosion and blast loading on framed building structures

3 Blast hazard assessment for natural-gas transmission pipelines

In the event of rupture of a high-pressure natural-gas pipeline, a large amount of flammable gas is rapidly released, generating formation and dispersion of a vapour cloud within air. If the cloud is ignited before it is diluted below its lower flammability limit, a vapour cloud explosion (VCE) occurs. From analysis of historical data, ignition delay times from 6 s to as long as 60 min were found by Lenoir and Davenport (1992); ignition delays from 1 to 5 min are considered the most probable for generating VCE (AIChE/CCPS, 1994).

Gas dispersion modelling is an essential part of hazard assessment. Among the models (empirical model, integral model, computational fluid dynamics – CFD) currently available for high-pressure jet release case, in this work a typical one-dimensional integral model named SLAB (Ermak, 1990) is used. That model uses the similarity
profiles that assume a specific shape for the crosswind concentration profile of the released gas and other properties. The downwind variations of spatially crosswind average concentration values are determined by using the conservation equations in the downwind direction only. The weakness of this type of model is that it cannot simulate the gas flow either around obstacles or over a complex terrain. The merit of the integral model is twofold: its computational cost is much less than that of CFD model and both the atmospheric condition and turbulence mixing can be taken into account. Nonetheless, in most integral models, such as SLAB, operation properties of high-pressure pipelines carrying the gas are usually missed.

For simulating the natural-gas jet release process from high-pressure pipeline, a C++ code was developed and incorporated within the SLAB one-dimensional integral model. The C++ code combines a release rate model (see equations (5) and (6)) with pipe operation properties (i.e. pipeline diameter, operating pressure), source release properties (i.e. hole diameter, length of pipeline from compression station), and site information (i.e. atmospheric stability, wind velocity, surface roughness).

The gas jet release was assumed to be horizontal and a steady-state plume with finite duration equal to 10 min. The release rate through a hole in the pipeline at steady state is estimated approximately by assuming choke flow at the release point (Jo and Ahn, 2002):

\[
Q_{\text{steady-state}} = \frac{Q_{\text{peak}}}{\sqrt{1 + \left(4 \alpha^2 f_F \frac{L}{d} \left(\frac{2}{\gamma + 1}\right)^{-\frac{1}{2}}\right)}}
\]

where \(f_F\) is the Fanning friction factor, \(L\) is the pipeline length from the gas supply station to the release point (in m), \(\alpha\) is the dimensionless hole size (i.e. the ratio of effective hole area to the pipe sectional area), \(d\) is the pipeline diameter (in m), \(\gamma\) is the specific heat ratio of gas and \(Q_{\text{peak}}\) is the peak initial release. The latter is estimated by assuming the sonic flow through an orifice as follows (Crowl and Louvar, 2011):

\[
Q_{\text{peak}} = \frac{\pi d^2 \alpha}{4} \sqrt{\rho_0 \rho_0 \frac{2}{\gamma + 1}}
\]

where \(\rho_0\) is the stagnation density of gas in operating conditions (in kg/m\(^3\)) and \(p_0\) is the stagnation pressure in operating conditions (in Pa).

The code determines the cloud extent corresponding to various pipeline operation properties, source release properties and site features. Statistical data of these parameters are required for assessing blast probability. Statistics for pipeline operation properties and source release properties are obtained by data of the EGIG (2013). Two different Pasquill atmospheric stability classes A (extremely unstable) and C (slightly stable) are considered. Wind velocities of 10, 20 and 30 m/s at a height of 10 m above ground are randomly produced, assuming a wind direction parallel to the gas jet and vertical logarithmic increase of wind velocity from the terrain roughness height. The latter (assumed equal to 0.003 m) is the height from ground above which wind velocity is rather uniform and equal to a minimum level that depends on several factors such as ground roughness and the amount and distribution of buildings and other facilities in the area.
The code then evaluates the consequences (i.e., overpressure and impulse) caused by the VCE according to the multi-energy method (TNO, 2005). The multi-energy concept assumes that only the part of combustion energy included in the flammable cloud, which is confined or obstructed, contributes to pressure generation in the explosion. In this way, the multi-energy model takes account of the positive feedback mechanism of a gas explosion. The amount of energy released during a VCE is limited either by the volume of the partially confined portion of the flammable vapour cloud or by the volume of the vapour cloud. In either case, the volume of the cloud within the partially confined space can be converted into a hemisphere of equal volume. Blast equations corresponding to blast charts are included in the model to determine the peak overpressure $\Delta P_p$ and positive phase duration $t_p$ from a family of equations (curves) relating a dimensionless overpressure to the combustion energy scaled distance. The ten blast strength equations (corresponding to TNO multi-energy curves) consist of positive pressure and time duration as functions of distance. The parameters were also normalised through the Sach’s scaling law with pressure, distance, and positive phase duration. Equation (7) defines the dimensionless overpressure $\Delta P'_p$ as peak overpressure divided by atmospheric pressure $p_a$ (in Pa):

$$\Delta P'_p = \frac{\Delta P}{p_a}$$

Based on the sound velocity $c_o$ (in m/s) and the combustion energy $E$ contributing to the fuel-air charge (in J), equations (8) and (9) allow a scaled positive phase duration $t'_p$ and a scaled distance to be determined as follows:

$$t'_p = \frac{t_p}{\left(\frac{E}{p_a}\right)^{\frac{1}{3}}/c_o}$$

$$R' = \frac{R}{\left(\frac{E}{p_a}\right)^{\frac{1}{3}}}$$

where $R$ is the distance from the (pipeline) blast centre (in m).

The explosion parameters $\Delta P_p$ and $t_p$ at a given distance $R$ from the explosion source are calculated from the scaled values associated with blast strengths 6 and 9. Finally, the positive impulse $I$ (in Pa s) is evaluated by integrating the overpressure variation over the positive phase duration. That integral is approximated as follows:

$$I = \frac{1}{2} \Delta P_p t_p$$

In total, $10^6$ simulations were run by varying the pipeline operation properties and source release properties in the following ranges according to statistical data: $d = 0.127–1.257$ m, $p_0 = 2000–8500$ kPa, $L = 50–10,000$ m, $d_{hole} = 0.02$ m–$d$, $R = 10–2000$ m, stability class = A–C, and wind velocity $v = 10–30$ m/s.
Figures 2‒5 show the effect of pipeline operation properties on the blast wave parameters in case of blast strength 6, atmospheric stability class C and \( v = 10 \text{ m/s} \). The same trend was observed in case of explosion class 9. The results are reported in terms of peak overpressure (Figure 2 (a)) and impulse (Figure 2 (b)) as functions of hole diameter, considering a pipeline-to-building distance \( R = 500 \text{ m} \), \( d = 1.257 \text{ m} \), \( L = 1000 \text{ m} \), and multiple levels of pipeline operating pressure \( p_0 \). Both blast wave parameters increased as hole diameter and operating pressure increase. Nevertheless, peak overpressure was more influenced by the hole size than operating pressure. The opposite occurred for impulse.

**Figure 2** (a) Peak overpressure and (b) impulse versus hole diameter at multiple levels of pipeline operating pressure \((d = 1.257 \text{ m}; L = 1000 \text{ m}; R = 500 \text{ m}; \text{ blast strength 6}; \text{ atmospheric stability class C}; v = 10 \text{ m/s}) (see online version for colours)
Figure 3 shows the peak overpressure and impulse, respectively, as functions of hole diameter at multiple pipeline diameters and fixed operating pressure ($p_0 = 5000$ kPa). As the pipeline diameter was increased, blast parameters increased and maximum levels of overpressure and impulse were associated with bore rupture.

On the contrary, when the distance of the release point from the compression station ($L$) was increased, both peak overpressure and impulse decreased because of the pressure reduction inside the pipeline (Figure 4). However, for the full-bore rupture of the pipeline, the blast parameters remained constant at about 500 m as the pipeline length $L$ gets longer than 3000 m, because the effective rate of gas release remained approximately constant (see equation (5)).
Similarly, as the distance from the pipeline \((R)\) was increased the blast wave parameters for full-bore rupture decreased significantly up to \(R = 1000\) m, where they get an almost constant level or their slope drastically reduces (Figure 5).

Finally, as far as the effect of atmospheric conditions is concerned, both stability and wind velocity reduced the blast wave parameters.

**Figure 4** (a) Peak overpressure and (b) impulse versus pipeline length from the gas supply station to the release point at multiple pipeline diameters \((p_0 = 5000\) kPa; \(R = 500\) m; full-bore rupture; blast strength 6; atmospheric stability class C; \(v = 10\) m/s) (see online version for colours)
Figure 5 (a) Peak overpressure and (b) impulse versus building distance from pipeline at multiple pipeline diameters ($p_0 = 5000$ kPa; $L = 1000$ m; full-bore rupture; blast strength 6; atmospheric stability class C; $v = 10$ m/s) (see online version for colours)

4 Blast capacity modelling and fragility of reinforced concrete columns

The capacity and fragility modelling for RC columns subjected to blast loading is a key module of probabilistic risk analysis. This study was focused on RC columns of existing European buildings designed to resist only gravity loads without any seismic detailing (Manfredi et al., 2007). The column prototype adopted for the evaluation of failure probability and safety distance had the following features: squared cross-section with nominal dimension of 300 mm and nominal concrete cover of 30 mm, nominal height equal to 3.00 m, concrete strength class C20/25, and reinforcing steel class B450C. Actually, the concrete strength class C20/25 and reinforcing steel class B450C
were, respectively, named as R$_{ck}250$ and FeB44K by Italian non-seismic codes in force since 1971 (Masi and Vona, 2012). The R$_{ck}250$ class indicated the value of the characteristic cube strength of concrete R$_{ck}$ in kg/cm$^2$. The reinforcing steel class FeB44K indicated the values of the characteristic yield strength of ribbed bars in $10^{-2}$ kg/cm$^2$. Squared cross-sections having dimension equal to 300 mm were typically adopted for RC columns located on the perimeter of low-rise and mid-rise residential buildings, namely those having no more than four storeys above ground. Nevertheless, columns with different sectional shape or cross-section can be detected in some cases and their blast fragility should be specifically evaluated. For instance, if the squared cross-section considered in this study is replaced by a rectangular cross-section with dimensions $300 \times 400$ mm$^2$, the median pressure asymptote increases of approximately 15%, whereas the median impulse asymptote increases of about 10% (Parisi, 2015). As such, a reduction in blast fragility should be taken into account to evaluate the corresponding safety distance.

After a two-component vector engineering demand parameter $EDP = [\Delta P_s, I]$ was computed to measure the intensity of the explosion event $E$ (see Section 3), blast capacity of RC columns was modelled through the following pressure–impulse equation (Shi et al., 2008):

$$
(\Delta P_s - P_0)(I - I_0) = 12\left(\frac{P_0}{2} + \frac{I_0}{2}\right)^{1.5}
$$

(11)

where $P_0$ and $I_0$ are the overpressure and impulse asymptotes corresponding to the column properties and the limit state of interest. The pressure–impulse diagram is the graphical representation of the combinations of peak overpressure and impulse that produce the same level of damage to the structural component. It is emphasised that the blast capacity model adopted in this work is based on the assumption of uniform peak overpressure along the column height. This is consistent with the pressure field associated with unconfined gas explosions. The limit state was directly associated with blast damage through a damage index defined as follows:

$$
D = 1 - \frac{N_{ad}}{N_{ud}}
$$

(12)

where $N_{ad}$ and $N_{ud}$ are the initial and residual load-bearing capacities of the RC column, respectively. According to equation (12), $D$ quantifies the blast damage to the column in terms of axial load-bearing capacity degradation. The initial load-bearing capacity is the ultimate axial load assumed in design. The residual load-bearing capacity is the ultimate axial load that is still available after that the blast load strikes the column. The limit state is reached if the damage index corresponding to $EDP$ equals or exceeds the threshold damage index $D_{LS}$. The value of $D$ associated with $EDP$ is estimated through a damage analysis where the distances between the demand point and the pressure–impulse diagrams corresponding to different limit states are computed. Three limit states associated with as many damage levels are usually defined as follows:

LS1 (slight damage): $D_{LS} = 0.2$

LS2 (moderate damage): $D_{LS} = 0.5$

LS3 (heavy damage/near collapse): $D_{LS} = 0.8$
The pressure and impulse asymptotes corresponding to each performance limit state depend on column properties and were evaluated through the following equations:

\[ P_i (LS1) = 1000 \left[ 0.007 \exp \left( \frac{\rho_s}{0.01} \right) + 0.069 \left( \frac{\rho}{0.01} \right) + 0.034 \exp \left( \frac{f_c}{30} \right) \right] - 0.835 \ln \left( \frac{H}{4.0} \right) + \left( \frac{h}{0.6} \right)^{1.304} + 0.067 \ln \left( \frac{b}{0.6} \right) - 0.168 \]

\[ I_i (LS1) = 1000 \left[ 0.053 \exp \left( \frac{\rho_s}{0.01} \right) + 0.107 \left( \frac{\rho}{0.01} \right) + 0.021 \exp \left( \frac{f_c}{30} \right) \right] + \left( \frac{H}{4.0} \right)^{-0.207} + 1.203 \exp \left( \frac{h}{0.6} \right) - 0.943 \ln \left( \frac{b}{0.6} \right) - 2.686 \]

\[ P_i (LS2) = 1000 \left[ 0.143 \ln \left( \frac{\rho_s}{0.01} \right) + 0.320 \ln \left( \frac{\rho}{0.01} \right) + 0.063 \exp \left( \frac{f_c}{30} \right) \right] + \left( \frac{H}{4.0} \right)^{-1.390} + 2.639 \left( \frac{h}{0.6} \right) + 0.318 \ln \left( \frac{b}{0.6} \right) - 2.271 \]

\[ I_i (LS2) = 1000 \left[ 0.837 \left( \frac{\rho_s}{0.01} \right) + 0.036 \left( \frac{\rho}{0.01} \right) + 0.235 \exp \left( \frac{f_c}{30} \right) \right] + \left( \frac{H}{4.0} \right)^{-0.274} + 2.271 \exp \left( \frac{h}{0.6} \right) - 0.998 \ln \left( \frac{b}{0.6} \right) - 5.286 \]

\[ P_i (LS3) = 1000 \left[ 0.062 \ln \left( \frac{\rho_s}{0.01} \right) + 0.238 \left( \frac{\rho}{0.01} \right) + 0.291 \ln \left( \frac{f_c}{30} \right) \right] - 1.676 \ln \left( \frac{H}{4.0} \right) + 2.439 \left( \frac{h}{0.6} \right) + 0.210 \ln \left( \frac{b}{0.6} \right) + 1.563 \]

\[ I_i (LS3) = 1000 \left[ 3.448 \left( \frac{\rho_s}{0.01} \right) - 0.254 \left( \frac{\rho}{0.01} \right) + 1.200 \left( \frac{f_c}{30} \right) \right] - 0.521 \left( \frac{H}{4.0} \right) + 6.993 \left( \frac{h}{0.6} \right) - 2.759 \ln \left( \frac{b}{0.6} \right) - 2.035 \]

where \( f_c \) is the concrete compressive strength (in MPa), \( H \) is the column height (in m), \( h \) is the cross-section depth of column (in m), \( b \) is the cross-section width of column (in m), \( \rho \) is the longitudinal reinforcement ratio, and \( \rho_s \) is the transverse reinforcement ratio. Strain rate effects, namely the dynamic increase in material strengths, were taken into account as they are indirectly considered in pressure–impulse diagrams.

Blast fragility of RC columns was computed through standard MC simulation, which consisted of the following steps:

Random generation of \( N_S \) column samples (or simulation realisations) according to probability distributions for material properties, column dimensions, reinforcement ratios, and capacity model error.
Damage analysis of each column sample performed in the \( P-I \) space to assess whether a prescribed amount of damage was reached or not.

Blast fragility computation at different \( EDP \) levels.

Details on this procedure for blast loads were presented by Parisi (2015). A vector of random variables (RV) \( \Theta \) was defined to account for uncertainties associated with material properties, column size, reinforcement ratios, and capacity model. Based on probability density functions assigned to RVs, \( N_S \) samples of uncertain variables \( \Theta \) were randomly generated. Statistics for concrete and reinforcing steel strengths were gathered from a number of studies available in the literature (Masi and Vona, 2012; Verderame et al., 2001a; Verderame et al., 2001b) and the corresponding RVs were assumed to be lognormally distributed. In detail, the mean values of concrete cylinder strength and yield strength were, respectively, set to 28 MPa with coefficient of variation \( \text{CoV} = 31\% \) and 500 MPa with \( \text{CoV} = 8\% \). On the other hand, all geometrical properties were supposed to be normally distributed. The mean values of sectional dimensions and column height were assumed to be equal to their respective nominal values (i.e. 300 mm and 3 m) with \( \text{CoV} = 4\% \). Mean values of 0.59\% (Masi and Vona, 2012) and 0.20\% (Sezen and Moehle, 2004) with \( \text{CoV} = 5\% \) were assigned to longitudinal and transverse reinforcement ratios, respectively. A normally distributed error for blast capacity model was also considered as actual-to-theoretical ratios of pressure and impulse asymptotes, assuming mean equal to 1 and \( \text{CoV} = 4\% \) (Shi et al., 2008).

Blast capacity was then estimated for each simulation realisation, allowing damage analysis to be carried out and blast fragility to be computed as follows:

\[
\hat{Pr}[LD|E] = \frac{1}{N_S} \sum_{j=1}^{N_S} I_{LD,E} (\Theta_j)
\]

where \( I_{LD,E}(\Theta) \) is an index limit state function which was set to unity if the \( j \)-th realisation \( \Theta \) of the vector \( \Theta \) led to \( D \geq D_{LS} \) and to zero otherwise. Equation (16) provides an estimate of blast fragility as the expected value of \( I_{LD,E}(\Theta) \), the CoV of which is given by:

\[
\text{CoV}_{\hat{Pr}[LD|E]} = \sqrt{\frac{1 - \hat{Pr}[LD|E]}{N_S \hat{Pr}[LD|E]}}
\]

Figure 6 shows blast fragility surfaces of the case-study RC column at several limit states corresponding to increasing levels of blast damage. MC simulation results are consistent with the physical evidence that the conditional probability of failure increases with the pressure–impulse levels and reduces as the threshold damage level increases. Blast fragility surfaces for any other type of RC column can be derived according to the procedure proposed by Parisi (2015) by introducing a hybrid scalar EDP. The natural logarithm of the hybrid EDP may be defined, for instance, as a linear combination of natural logarithms of peak overpressure and impulse. In that case, different statistical methods such as the ordinary least squares and maximum likelihood estimation can be used to estimate the parameters of blast fragility surfaces. It is underlined that horizontal sections of blast fragility surfaces provide uniform-probability pressure–impulse diagrams that can be effectively used for performance-based blast-resistant design/assessment of RC columns.
Figure 6  Blast fragility surfaces of case-study RC columns at multiple limit states: (a) slight damage ($D_{LS} = 0.2$), (b) moderate damage ($D_{LS} = 0.5$), and (c) heavy damage/near collapse ($D_{LS} = 0.8$) (see online version for colours)
5 Annual risk of blast damage and safety distance

The convolution of blast fragility and hazard according to equation (4) allowed the authors to estimate the annual probability of damage \( \text{Pr}[E|R] \) for each limit state of interest and 1000 km of pipeline length.

The probability of damage for blast strength 9 and slightly stable atmospheric conditions (class C) was found to be \( 9.73 \times 10^{-3}/1000 \text{ km/year} \) at \( D_{LS} = 0.2 \), \( 8.15 \times 10^{-3}/1000 \text{ km/year} \) at \( D_{LS} = 0.5 \), and \( 2.47 \times 10^{-3}/1000 \text{ km/year} \) at \( D_{LS} = 0.8 \). Lower probability values were found for blast strength 6 (class C), namely \( 3.18 \times 10^{-5}/1000 \text{ km/year} \) at \( D_{LS} = 0.2 \), \( 3.09 \times 10^{-5}/1000 \text{ km/year} \) at \( D_{LS} = 0.5 \), and \( 1.19 \times 10^{-6}/1000 \text{ km/year} \) at \( D_{LS} = 0.8 \).

Tables 1 and 2 outline the annual risk of structural collapse (i.e. \( D_{LS} = 0.8 \)) per 1000 km of pipeline length in terms of peak overpressure and impulse, for blast strength 9 and stability classes A and C, respectively. Assuming slightly stable atmospheric conditions (class C) determined higher values of \( \text{Pr}[E|R] \) than unstable conditions (class A) because of the more unfavourable conditions for dilution of natural gas below flammability limits.

Table 1  Annual risk of heavy damage to RC columns \( (D_{LS} = 0.8) \) at different levels of peak overpressure and impulse (blast strength 9; atmospheric stability class A)

<table>
<thead>
<tr>
<th>Impulse (kPa·ms)</th>
<th>5000</th>
<th>12,500</th>
<th>17,500</th>
<th>30,000</th>
<th>60,000</th>
<th>140,000</th>
<th>300,000</th>
<th>532,500</th>
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<td>0</td>
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<tr>
<td>84</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.9 \times 10^{-6}</td>
<td>2.6 \times 10^{-7}</td>
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<td>119</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3.2 \times 10^{-8}</td>
<td>1.5 \times 10^{-6}</td>
<td>1.5 \times 10^{-6}</td>
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<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>6.6 \times 10^{-4}</td>
<td>1.2 \times 10^{-3}</td>
<td>5.2 \times 10^{-3}</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.4 \times 10^{-3}</td>
<td>5.4 \times 10^{-5}</td>
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<td>0</td>
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<td>0</td>
<td>7.8 \times 10^{-5}</td>
<td>0</td>
<td>4.4 \times 10^{-4}</td>
</tr>
</tbody>
</table>

Table 2  Annual risk of heavy damage to RC columns \( (D_{LS} = 0.8) \) at different levels of peak overpressure and impulse (blast strength 9; atmospheric stability class C)

<table>
<thead>
<tr>
<th>Impulse (kPa·ms)</th>
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<th>12,500</th>
<th>17,500</th>
<th>30,000</th>
<th>60,000</th>
<th>140,000</th>
<th>300,000</th>
<th>532,500</th>
</tr>
</thead>
<tbody>
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<td>84</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>2.9 \times 10^{-6}</td>
<td>6.8 \times 10^{-7}</td>
<td>1.3 \times 10^{-7}</td>
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<tr>
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<td>0</td>
<td>0</td>
<td>3.6 \times 10^{-8}</td>
<td>2.1 \times 10^{-6}</td>
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<tr>
<td>169</td>
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<td>0</td>
<td>0</td>
<td>1.8 \times 10^{-6}</td>
<td>2.4 \times 10^{-6}</td>
<td>2.0 \times 10^{-5}</td>
</tr>
<tr>
<td>249</td>
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<td>0</td>
<td>0</td>
<td>1.2 \times 10^{-5}</td>
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<tr>
<td>374</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>3.3 \times 10^{-5}</td>
<td>7.6 \times 10^{-5}</td>
<td>7.2 \times 10^{-3}</td>
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<tr>
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<td>0</td>
<td>7.3 \times 10^{-5}</td>
<td>0</td>
<td>7.1 \times 10^{-4}</td>
</tr>
</tbody>
</table>
In case of blast strength 6, the conditional probability of occurrence was found to be higher than $10^{-8}$ only for a blast demand level given by peak overpressure and impulse equal to $\Delta P_s = 19$ kPa and $I = 12,500–140,000$ kPa ms.

The blast hazard methodology also allowed the estimation of the blast radius of blast wave, defined as the maximum distance from the blast centre (pipeline) at which given values of overpressure and impulse are achieved. For both blast strengths (i.e. 6 and 9) and atmospheric conditions (i.e. classes A and C), a blast radius as high as 2000 m was found.

Assuming a threshold probability of structural collapse $p_{th} = 10^{-5}/1000 \text{ km/year}$, a minimum safety distance of the building from the natural-gas pipeline was derived. The threshold probability is the de minimis risk defining the acceptable risk level below which society normally does not impose any regulatory guidance. In case of blast strength 9, a minimum safety distance equal to 800 m for stability class A and 2300 m for stability class C was estimated. For the same atmospheric conditions, the minimum safety distance corresponding to blast strength 6 was estimated in 10 m.

Therefore, the convolution of blast hazard and fragility allows the derivation of iso-risk distances, namely minimum levels of pipeline-to-column distance below which the de minimis risk of a given damage level is reached or exceeded. That distance is significantly important for risk-informed urban planning.

### 6 Conclusions

In this study, a new procedure to estimate the annual probability of direct structural damage to RC framed buildings associated with high-pressure natural-gas pipeline explosions has been proposed.

Direct damage to those building structures was measured as axial load-bearing capacity degradation, according to a damage index defined by other researchers and successfully used in past studies. Probabilistic blast hazard and fragility analyses were carried out through Monte Carlo simulation. Blast hazard was evaluated by means of SLAB model and multi-energy method, in order to consider physical features of natural-gas leakage together with vapour cloud generation, propagation and ignition. Blast fragility surfaces have been plotted to graphically represent the conditional probability of failure for RC columns subjected to blast load hazard. Assuming a threshold probability of structural collapse for RC columns, a minimum safety distance between natural-gas pipelines and RC buildings was derived for risk-informed land-use planning. Safety distance was provided for RC columns of gravity-load designed residential buildings located in Southern Europe, high-pressure natural-gas pipelines, explosion classes 6 and 9, Pasquill atmospheric stability classes A and C, and three possible levels of wind velocity.

The probabilistic procedure presented herein may be used either to design/assess new pipeline networks close to existing building assets, or to design/assess new buildings with a given safety level against potential gas explosions. In the case of new buildings and pipelines, urban planners are recommended to check that the relative building-pipeline distance does not exceed the risk-targeted safety distance. Conversely, when assessing the structural safety of existing buildings, the designer should implement risk reduction
measures such as external strengthening of columns and protective barriers if the distance between the building structure and the pipeline is lower than the safety distance. The effects of other types of natural-gas pipelines and blast fragility of other types of structures, such as steel framed buildings, RC bridges, and masonry buildings, need to be investigated. It is also emphasised that the safety distance presented in this study is associated with a given shape and size of RC columns, so it should be evaluated for columns other than those considered by the authors of this paper.

References


